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The Influence of Robotic Assistance on Reducing Neuromuscular Effort and Fatigue during Extravehicular Activity Glove Use

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The three-layered, pressurized space suit glove worn by Extravehicular Activity (EVA) crew members during missions commonly causes hand and forearm fatigue. The Spacesuit RoboGlove (SSRG), a Phase VI EVA space suit glove modified with robotic grasp-assist capabilities, has been developed to augment grip strength in order to improve endurance and reduce the risk of injury in astronauts. The overall goals of this study were to i) quantify the neuromuscular modulations that occur in response to wearing a conventional Phase VI space suit glove (SSG) during a fatiguing task, and ii) determine the efficacy of Spacesuit RoboGlove (SSRG) in reversing the adverse neuromuscular modulations and restoring altered muscular activity to barehanded levels. Six subjects performed a fatigue sequence consisting of repetitive dynamic-gripping interspersed with isometric grip-holds under three conditions: barehanded, wearing pressurized SSG, and wearing pressurized SSRG. Surface electromyography (sEMG) from six forearm muscles (flexor digitorum superficialis (FDS), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor digitorum (ED), extensor carpi radialis longus (ECRL), and extensor carpi ulnaris (ECU)) and subjective fatigue ratings were collected during each condition. Trends in amplitude and spectral distributions of the sEMG signals were used to derive metrics quantifying neuromuscular effort and fatigue that were compared across the glove conditions. Results showed that by augmenting finger flexion, the SSRG successfully reduced the neuromuscular effort needed to close the fingers of the space suit glove in more than half of subjects during two types of tasks. However, the SSRG required more neuromuscular effort to extend the fingers compared to a conventional SSG in many subjects. Psychologically, the SSRG aided subjects in feeling less fatigued during short periods of intense work compared to the SSG. The results of this study reveal the promise of the SSRG as a grasp-assist device that can improve astronaut performance and reduce the risk of injury by offsetting neuromuscular effort. Modifications to the experimental protocol are needed, however, to improve the outcome of the neuromuscular fatigue metrics and determine the effectiveness of SSRG in increasing astronaut endurance. Nevertheless, these findings will improve the understanding of astronaut-spacesuit interaction and provide direction toward designing improved spacesuit gloves and robotic-assist devices, like the SSRG.

Nomenclature

Bare = barehanded condition

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ECRL	=	extensor carpi radialis longus
ECU	=	extensor carpi ulnaris
ED	=	extensor digitorum
EVA	=	extravehicular activity
FCR	=	flexor carpi radialis
FCU	=	flexor carpi ulnaris
FDS	=	flexor digitorum superficialis
iEMG	=	integrated electromyography
MF	=	median frequency of the sEMG power spectral density
MVC	=	maximum voluntary contraction
sEMG	=	surface electromyography
SSG	=	conventional Phase VI space suit glove
SSRG	=	Spacesuit RoboGlove

I. Introduction

THE future of space exploration relies upon the ability of astronauts to perform hand intensive tasks, such as ~~shuttle~~ construction, service, and repair of the International Space Station (ISS), during extravehicular activity (EVA) missions. Although the Phase VI EVA glove contains the most advanced spacesuit glove technology to date, its cumbersome three layer design considerably reduces finger mobility and hand grip strength.[1-4] These decrements are further exacerbated by the presence of a 4.3 psi spacesuit pressure differential.[1-3] The internal pressure inflates the space suit and causes the glove to adopt a preferred orientation where the fingers are almost fully extended. In order to flex the fingers, astronauts must exert considerable effort to fight against the natural tendency of the glove fingers to remain extended[5]. This is a primary reason why hand, finger, and forearm fatigue are amongst the top three most common types of injuries endured by astronauts during EVA missions.[2,6,7] Spacesuit glove-induced fatigue can negatively impact astronaut performance by decreasing their efficiency in completing a task and reducing productivity during EVA missions.[2] More importantly, fatigue reduces astronaut endurance and induces high levels of muscular effort, which heightens the risk of developing overuse injuries.

The Spacesuit RoboGlove (SSRG),[8,9] a Phase VI spacesuit glove modified with robotic grasp assist capabilities, has been developed to improve astronaut endurance and reduce the risk of injury during EVA missions. The device works to both combat the pressure differential of the space suit by aiding astronauts in closing their hands and increasing their grip strength.[8,10] The SSRG has tendons that connect to linear actuators located around the forearm, route along the palm of the hand, and attach to the distal segments of the index, middle, ring, and pinky fingers. (The current version of SSRG does not include thumb actuation.) Two different types of sensors contribute to different control modes that robotically aid in finger flexion. Force sensitive resistors (FSR), located on the finger pads of the SSRG, detect an interaction force between the fingers and a grasped object. When the force exceeds a threshold value, a command is sent to the motors to pull the tendons, drawing the fingers closer to the palm.[8-10] The motors will remain engaged and continue to flex the fingers until the detected force drops below the threshold value. The motors will then release and the fingers will be allowed to fully extend. This control mode is beneficial for a task that requires maintaining a constant grip on an object. String potentiometers, located on the back of the wrist, detect the relative linear position of the user's fingers. When the user initiates finger flexion, the string potentiometers sense a change in position of the finger and a command is sent to the motors to pull the tendon and assist in flexion. This control strategy is similar to a power steering mechanism in that the motors only assist the user when he/she is exerting a force on the glove to flex or extend. If the user does not exert a force, the system does not provide any assistance. Unlike the FSR based control mode, this mode does not return the fingers back to full extension after the user stops commanding the glove. Rather, the glove fingers remain in their last commanded position until the string potentiometer detects the user's next intended motion. This control mode is beneficial for a task that requires repetitive movement of the fingers. A preliminary study has shown that the SSRG can consistently augment the user's grip strength using the FSR based control mode,[8] however, further analysis is needed to evaluate its potential to reduce neuromuscular effort and fatigue using both control modes.

Muscle fatigue is defined as a decrease in the force generating capacity of a muscle or group of muscles after an activity.[11,12] Current practice for evaluating spacesuit glove-induced fatigue is to use a questionnaire or analog scale to rate the amount of fatigue experienced after performing a task. This subjective score is representative of a subject's psychological perception of fatigue and is, therefore, biased toward his or her mental state. Another popular method of assessing fatigue is to measure performance decline, or mechanical failure, based on when a subject becomes unable to sustain a desired force. However, this method can also be influenced by the subject's psychological state and motivation.[2,13] A third technique uses surface electromyography (sEMG) to measure physiological, or metabolic, fatigue.[2] The signal detected using sEMG represents the summation of the electrical activity of the underlying muscle motor units (MUs).[14] A peripheral response to fatigue is a buildup of lactates and metabolites that slow the propagation of motor unit action potentials, called the conduction velocity (CV), along the muscle fibers.[12,15] The decline in muscle fiber CV causes a compression of the sEMG signal's power density spectrum.[16] This shift can be detected by a decrease in the median frequency (MF), the frequency that divides the power spectrum into two regions of equal power.[11] Since this technique is performed individual muscles, it allows for a more comprehensive analysis concerning which muscles are most affected by fatigue and how the fatigue manifests over time.

Neuromuscular effort provides important insight into the magnitude of each muscles relative contribution to a given work output. The integrated EMG (iEMG) of a sEMG signal is commonly used as a quantitative index of expended effort[17] and is a measure of the cumulative amplitude of a muscles sEMG signal. It provides a measure of the amount of neural energy required to produce or maintain a level of muscular tension[18] because it directly varies with tension exerted.[4] When a muscle has to expend high levels of effort during a task, it is predisposed to becoming fatigued. Thus, neuromuscular effort can be used as a presage of fatigue.

The overall goals of this study were to i) quantify the neuromuscular modulations that occur in response to wearing a conventional Phase VI space suit glove (SSG) during a fatiguing task, and ii) determine the efficacy of Spacesuit RoboGlove (SSRG) in reversing the adverse neuromuscular modulations and restoring altered muscular activity to barehanded levels. The results of this study will improve the understanding of astronaut-spacesuit interaction, identify the beneficial and adverse neuromuscular effects of integrating a robotic-assist device into the space suit architecture, and inform engineers of how to better design spacesuit gloves and robotic assist devices, like the SSRG, to reduce muscle workload and combat fatigue.

II. Methods

A. Subjects

Six NASA civil servants (age = 30 ± 3.75 years, maximum grip strength = 119 ± 20 lbs) with varying levels of experience wearing spacesuit gloves participated in this study. All subjects recruited for this study were male to eliminate potentially confounding gender effects[3] on EVA glove performance. The subject pool was restricted to individuals whose hand closely fits the NF-sized Phase VI EVA Space Suit glove by ILC Dover, Inc since the SSRG (Fig.1) is currently only available in one size. Fit was evaluated based on hand and finger measurements as well as fingertip and crotch pressure in the glove. All subjects were right hand dominant and asymptomatic of musculoskeletal disorders affecting the assessed distal upper extremity, as determined by a Modified Nordic Questionnaire.[19] Each subject provided institutionally-approved written informed consent prior to their participation in this study. All subject data were collected in the Advanced Suit Laboratory (ASL) at NASA Johnson Space Center (JSC) in Houston, TX.

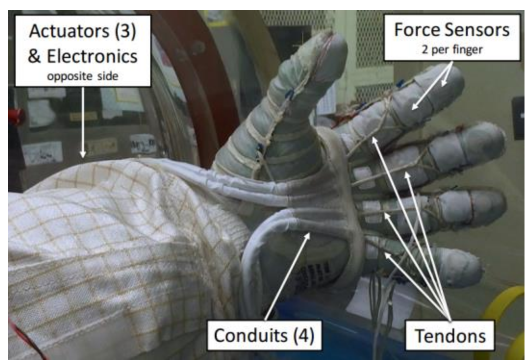

Figure 1. Photograph of Spacesuit RoboGlove.

B. Experimental Design

A repeated-measures study design was used to examine the differences between the amount of neuromuscular effort and fatigue induced by three different glove conditions: barehanded (Bare), wearing a Phase VI space suit glove (SSG) pressurized to 4.3 psi, and wearing Spacesuit RoboGlove (SSRG) pressurized to 4.3 psi. All conditions were performed in a glove box (Fig. 2), a vacuum chamber used to simulate pressure differentials for evaluating EVA glove performance without donning the entire space suit, located in the ASL. Since the experiment only tested the right hand, subjects wore a Phase VI space suit glove on their left hand during the SSG and SSRG conditions to maintain the seal of the glove box chamber. Since the Bare condition did not require glove box pressurization, subjects used their bare left hand during this condition.

Each subject participated in three sessions, one for each glove condition, held on three consecutive days. Subjects were given approximately 24 hours of rest between sessions to minimize the effects of residual fatigue from a previous session. The order of the three conditions was pseudo-randomized. The barehanded condition was always performed during the first session to allow the subject to become thoroughly acquainted with the task and minimize learning effects during the following gloved conditions. The remaining two glove conditions were counterbalanced such that three of the subjects performed the SSG condition during session two and SSRG condition during session three, while the other three subjects performed these conditions in opposite order.

Before each session, the glove box was adjusted to the height of the subject. The subjects positioned themselves in the glovebox such that their forearm was in a neutral posture (i.e. their ulna bone was resting on the bed of the glovebox with the radius bone oriented directly on top of it (Fig. 2)) and their weight was equally distributed across both legs. To obtain a baseline-rest reference signal for data processing, subjects remained motionless in this posture while 5s worth of sEMG data was collected. To obtain a maximum-level reference signal for data normalization, the subjects performed three barehanded maximum voluntary contractions (MVCs) using a hand dynamometer with their forearm in the neutral posture. Regardless of which session was being performed that day, all MVC's were executed barehanded to ensure that the data collected each day could be normalized to a value consistent across all glove conditions. Each MVC lasted for 5 s with three minutes rest in between contractions. Subjects were provided with visual force feedback and strong verbal encouragement to maximize their performance. The maximum force value from the set of MVCs was used to calculate the prescribed force requirement used during the fatigue sequence. Before the fatigue sequence began, subjects were given time to practice manipulating the hand dynamometer and gripper in accordance with the experimental protocol, described below. Additionally, the SSRG session required a brief calibration period to optimize and personalize its control strategy to the subject.

Figure 2. Experimental setup showing a subject wearing the SSRG and squeezing a dynamic gripper inside of the glove box.

An experimental protocol previously used to evaluate the effects of space suit glove pressurization on muscle fatigue and work[2] was adopted for this study to allow for validation and comparison of our results. The motivation behind the experimental design was to use isometric contractions to take snap shots of a subject's fatigued state as they performed a dynamic fatiguing task. This type of design is necessary to accommodate the non-stationarity of the sEMG signals, a property that affects spectral analysis and MF calculations.[20,21] The fatigue protocol consisted of six total trials, referred to as Trials 0-5. Each trial began with a 10 s isometric task (constant-force contraction) followed by 60s of a dynamic task (cyclic-gripping contractions), all of which were performed with the forearm in the neutral position.

The isometric tasks were executed at 20% of the subject's largest MVC force value using a hand dynamometer. Subjects were given visual feedback displaying the desired (20% MVC) force threshold they needed to maintain and their actual force output with the hand dynamometer. After the 10s isometric task was completed, the subjects verbally announced a real-time subjective fatigue rating. This rating, based on a five-point analog scale that ranged from 1 (no noticeable fatigue) to 5 (complete fatigue), aimed to assess their psychological perception of fatigue. To ensure subject safety, if a subject reported subjective fatigue ratings of '5' for two consecutive trials, he/she would not perform the subsequent dynamic task. It was only necessary to enforce this precautionary measure for one subject who felt too fatigued to perform the final (Trial 5) dynamic contraction of the SSG condition.

The subjects then transitioned to the dynamic task. Since it is very difficult to manipulate tools while wearing a space suit glove, 8 s were allotted for the subjects to set down the hand dynamometer and pick up the custom-built dynamic gripper (Fig. 2). Using the gripper set to approximately 5 lbs of resistance, cyclic-gripping contractions were performed at a 2 Hz cadence in time with a metronome. Subjects took one second to open and one second to close the device for a total of 30 squeezes in 60 s. The end of the dynamic task marked the end of a trial, and subjects were given 8 s to transition back to the hand dynamometer to prepare for the isometric task of the next trial. Upon completion of the fatigue protocol, subjects were assessed for the overall effect of fatigue on their task performance.[2] The subjects answered a series of questions that correlated to a global fatigue rating that ranged from 0 (no fatigue was experienced) to 8 (fatigue substantially affected performance).

C. Data Collection

An NI 9035 CompactRIO, NI 9205 and NI 9237 I/O modules, and LabVIEW software (National Instruments, Inc., Austin, TX) were used to program the fatigue protocol and synchronously collect sEMG and force data. A

JAMAR A/D hydraulic hand dynamometer was used to collect force data during the MVC and isometric tasks. The analog output signal from the hand dynamometer was connected to the NI 9237 module, a unit that provides signal conditioning for strain gauges and sampled at just over 1000 Hz. The analog output signals from the sEMG system were connected to the analog input channels of the NI 9205 module and sampled at just over 1000 Hz. sEMG data were collected, using a 16-channel Delsys Trigno Wireless EMG system with Trigno Mini sensors (Delsys Inc., Boston, MA), from six muscles of the right forearm: flexor digitorum superficialis (FDS), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor digitorum (ED), extensor carpi radialis longus (ECRL), and extensor carpi ulnaris (ECU). To prepare for sEMG electrode placement, each subject's forearm was shaved, and the skin was lightly abraded and cleansed with isopropyl alcohol. Electrodes were placed along the longitudinal midline of the muscle, oriented parallel to the long axis of the muscle fibers, and aimed to avoid muscle innervation zones based on locations reported in the literature.[4,22,23] A bandage was wrapped around the electrodes to secure the electrodes tightly against the muscles and prevent possible dislodging from the skin. A second sleeve was placed over the bandage to reduce the friction between the inside of the spacesuit gloves and the bandage as the subject rotates his forearm within the glove. After each session, electrode locations were marked on the skin to ensure consistent sensor placement across the three day experimental period. Real-time subjective fatigue ratings between 1 and 5 were verbally reported by the subjects and manually recorded by the experimental administrator. GoPro cameras (GoPro, Inc.) were used to take video recordings during the sessions. Global fatigue ratings between 0 and 8 were collected at the end of each session.

D. Data Processing

1. Force Recordings

All data were processed and analyzed using Matlab (The Mathworks, Natick, MA). Raw force data from the hand dynamometer were resampled to exactly 1000 Hz, low pass filtered with a cutoff frequency of 6 Hz using a 6th order Butterworth filter, and multiplied by the manufacturer's calibration constants. The force profiles were analyzed to identify the time at which the subjects reached and maintained, with minimal overshoot, their respective 20% MVC force values during the isometric tasks. This information was used to truncate the signal for neuromuscular fatigue analysis.

2. Surface Electromyography

All raw sEMG signals from each muscle were resampled to exactly 1000 Hz, bandpass filtered from 20 to 400 Hz using a 6^{th} order zero-lag non-causal Butterworth filter, high pass filtered with a cutoff frequency of 6 Hz using a 6^{th} order zero-lag non-causal Butterworth filter to remove baseline drift, and de-meaned to remove DC offset.

For analysis of neuromuscular effort, sEMG signals from the MVC, isometric, and dynamic tasks were full-wave rectified and root-mean-square (RMS) converted using a 100 ms moving window. The amplitude of the baseline-rest sEMG was quadratically subtracted from all other sEMG signals collected during the experiment to correct for noise. The sEMG amplitude from the largest MVC was used to normalize the signals. Integrated EMG (iEMG) of each signal was calculated by integrating the normalized RMS amplitude over the length of the task. iEMG was then time normalized to the length of each task.

For analysis of neuromuscular fatigue, sEMG signals for each isometric trial were filtered using an adaptive filter[24-26] to remove the 60 Hz power line interference. The sEMG signals were truncated to exclude the first two seconds and last second worth of data. This corrected for the amount of time it took subjects to reach and maintain their prescribed 20% MVC force value and ensured that the sEMG signal being analyzed could satisfy stationarity criteria because it corresponded to a constant force output. The signal was then divided into shorter 500 ms epochs with 20% overlap so that it could be considered a wide-sense stationarity stochastic process[20,21] upon which the power spectral density can be computed. The power spectrum was estimated from each epoch using a 6^{th} order autoregressive (AR) model[20,21,27] of the form:

$$x(n) = -\sum_{k=1}^{p} a_k x(n-k) + e(n) \tag{1}$$

with Burg's maximum entropy spectral estimation.[28] In Eq. (1), *x(n)* are the samples of the modeled sEMG signal, a_k are the AR coefficients, *k* are the reflection coefficients, *e(n)* is the residual error, and *p* is the model order. This parametric approach avoids many of the limitations of a Fourier based analysis that negatively affect spectral estimates.[21] The median frequency (MF) of each epoch was estimated by finding the frequency that divided the power spectral density, P(f), into two parts of equal areas using the equation:

$$\int_0^{MF} P(f)\,\mathrm{d}t = \int_{MF}^{\infty} P(f)\,\mathrm{d}t = 0.5\int_0^{\infty} P(f)\,\mathrm{d}t \tag{2}$$

A least-squares best-fit line was fit to the time series of MF values during a given trial, from which the y-intercept value was extracted. This process was repeated so that a y-intercept MF value was calculated for every isometric trial. The y-intercept values of Trials 1-5 were normalized to the y-intercept of Trial 0,[29] which is considered to be the subjects unfatigued state. The cumulative effects of fatigue were then compared for each glove condition by measuring the change in initial values of MF over each trial.[13,20,29]

E. Statistical Analysis

All statistical analyses were performed in R 3.3.2.[30] To evaluate modulations in expended neuromuscular effort in response to changes in glove condition (Bare, SSG, SSRG) a two-way (glove condition, muscle) repeated measures analysis of variance (rmANOVA) was used. To evaluate differences in subjective fatigue ratings in response to changes in glove condition (Bare, SSG, SSRG) a two-way (glove condition, trial) rmANOVA was used. Significant main and interaction effects were adjusted using a Huynh-Feldt correction for sphericity violations and examined using post-hoc pairwise comparisons with a Bejamini-Hochberg correction for multiple comparisons. The adjusted criterion for statistical significance and marginal statistical significance were set at $p<0.05$ and $p<0.1$, respectively.

To determine the strength of relations between variables while accounting for dependent samples, linear mixed effects models were implemented using a single fixed effect predictor with a random effect for slope varying by subject. Conditional R-squared values, which indicate the proportion of variance explained by both the fixed and random factors, were computed. Although conditional R-squared values are reported, all analyses revealed positive linear relationships which allowed for direct calculation of the correlation coefficients, r. Outliers were detected using Tukey's method and eliminated. This analysis was performed to determine if global subjective fatigue ratings could be predicted based on neuromuscular effort, if muscular effort required for the dynamic task could be predicted based on the effort required during the isometric task, and if muscular effort of one muscle could be predicted by another muscle during the same task.

III. Results

A. Neuromuscular Effort

Normalized iEMG during the isometric task resulted in significant main effects associated with glove condition ($p = 0.002$) and significant glove*muscle interaction effects ($p=0.004$) (Fig. 3). Post-hoc analyses revealed that, regardless of muscle, both the SSG and SSRG resulted in higher normalized iEMG values compared to barehanded work ($p = 0.011$ and $p = 0.018$, respectively). No significant differences between SSG and SSRG were found. FDS displayed higher iEMG during the SSG and SSRG conditions compared to barehanded work ($p=0.064$ and $p=0.078$, respectively). FCR displayed higher iEMG during SSG work compared to barehanded work ($p=0.087$). ED displayed higher iEMG during the SSG and SSRG conditions compared to barehanded work ($p = 0.064$ and $p=0.064$, respectively); and higher iEMG was displayed while wearing the SSRG compared to SSG ($p=0.067$). ECRL displayed higher iEMG for the SSG and SSRG compared to barehanded work ($p=0.074$ and $p=0.81$, respectively). Normalized iEMG data during the dynamic condition did not result in any significant main effects associated with glove condition, however, marginally significant glove*muscle interaction effects were revealed (Fig. 3). FDS displayed higher iEMG during the SSG and SSRG conditions compared to barehanded work ($p=0.081$ and $p=0.081$, respectively). FCU displayed higher iEMG was during SSG work compared to barehanded work ($p=0.086$). The grand means of the normalized iEMG are displayed in Table 1. An example of variation in subject response to wearing the SSRG is displayed in Fig. 4.

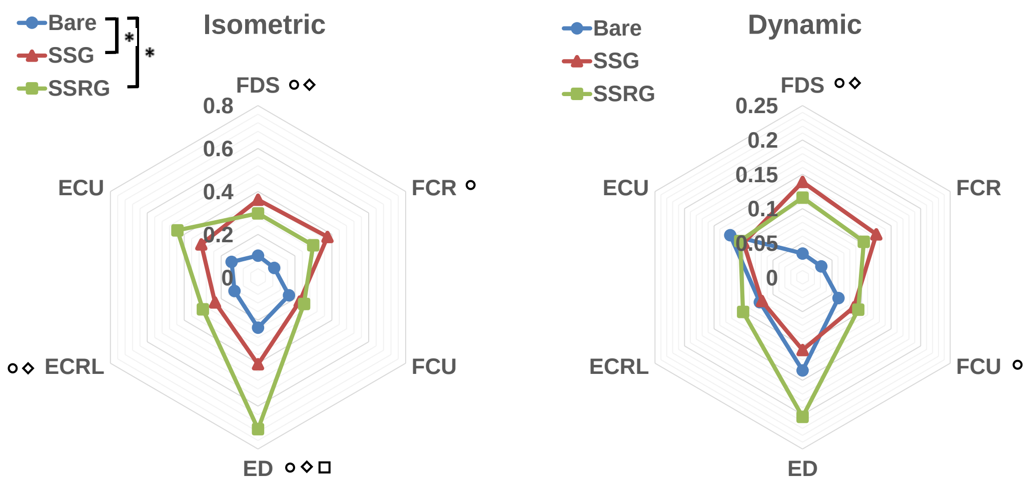

Figure 3: Neuromuscular effort exerted during isometric and dynamic tasks. Differences in muscular effort exerted during the isometric (left) and dynamic (right) tasks as assessed by the normalized iEMG (unitless) averaged over the six trials. Values are means taken across all subjects for the FDS, FCR, FCU, ED, ECRL, and ECU during barehanded (Bare), SSG, and SSRG work. iEMG mean values and standard deviations are reported in Table 1. Significant ($p<0.05$) post hoc results are indicated for pairwise comparisons between Bare and SSG conditions (●), Bare and SSRG (♦), and SSG and SSRG (■). Marginally significant ($p<0.1$) post hoc results are indicated for pairwise comparisons between Bare and SSG (○), Bare and SSRG (◊), and SSG and SSRG (□). Significant ($p<0.05$) glove main effects are indicated (*) in the legend.

Task	Group	Muscle	BARE	SSG	SSRG
Isometric	Flexors	FDS	0.10 ± 0.01	0.36 ± 0.06	0.30 ± 0.06
		FCR	0.09 ± 0.00	0.38 ± 0.10	0.30 ± 0.11
		FCU	0.17 ± 0.04	0.23 ± 0.03	0.25 ± 0.06
	Extensors	ED	0.23 ± 0.02	0.41 ± 0.03	0.71 ± 0.11
		ECRL	0.13 ± 0.02	0.23 ± 0.05	0.30 ± 0.07
		ECU	0.14 ± 0.01	0.31 ± 0.08	0.44 ± 0.13
Dynamic	Flexors	FDS	0.03 ± 0.00	0.14 ± 0.02	0.12 ± 0.02
		FCR	0.03 ± 0.00	0.12 ± 0.02	0.10 ± 0.02
		FCU	0.06 ± 0.01	0.09 ± 0.01	0.09 ± 0.02
	Extensors	ED	0.14 ± 0.01	0.11 ± 0.02	0.20 ± 0.07
		ECRL	0.07 ± 0.02	0.07 ± 0.02	0.10 ± 0.03
		ECU	0.12 ± 0.03	0.10 ± 0.05	0.11 ± 0.01

Table 1. Glove related differences in neuromuscular effort. Changes in neuromuscular effort, reported as normalized iEMG averaged across trials, in flexor and extensor muscles (FDS, FCR, FCU, ED, ECRL, and ECU) as a result of different glove conditions: BARE (barehanded), SSG (Phase VI space suit glove), and SSRG (Spacesuit RoboGlove). Results are reported for both the isometric and dynamic tasks. Values are means ± standard deviations.

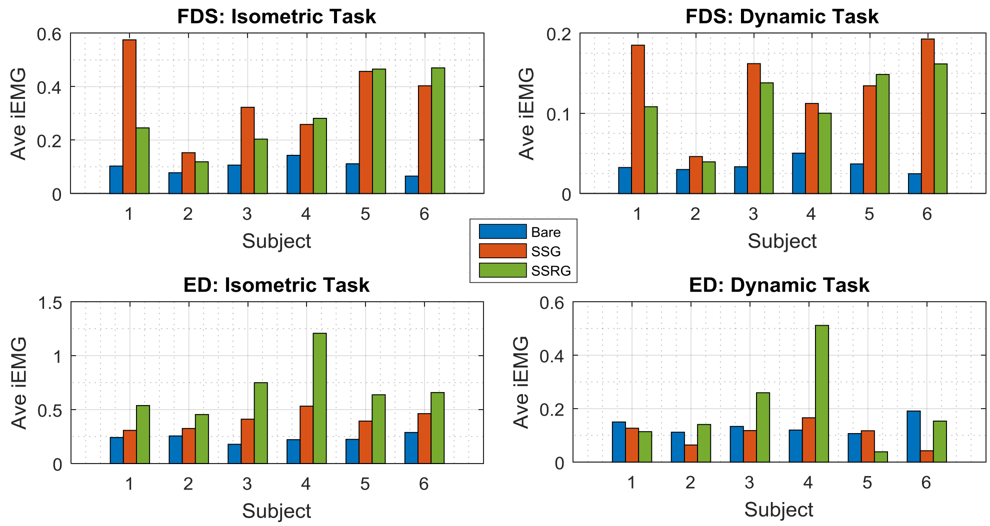

Figure 4: Variation in neuromuscular effort (iEMG) across subjects. Differences in muscular effort exerted by the FDS and ED muscles of each subject during the isometric (left) and dynamic (right) contraction tasks, as assessed by the normalized iEMG (unitless) averaged over the six experimental trials during barehanded (Bare), SSG, and SSRG work.

B. Subjective Fatigue

Statistically significant differences between glove conditions (Bare, SSG, and SSRG) were not found for the real-time subjective fatigue ratings collected over the six trials. However, subjects rated the SSRG condition as less fatiguing than the SSG condition and equally as fatiguing as the barehanded condition during Trials 0-2 (Fig. 5). During Trials 3-5, however, subjects rated the SSRG and SSG as equally as fatiguing (Fig. 5). Global fatigue ratings (Fig. 5), which were analyzed separately from the real-time ratings, showed that subjects rated the SSG and SSRG as more fatiguing than barehanded work ($p=0.017$ and $p=0.013$, respectively). Statistically significant differences between SSG and SSRG were not found.

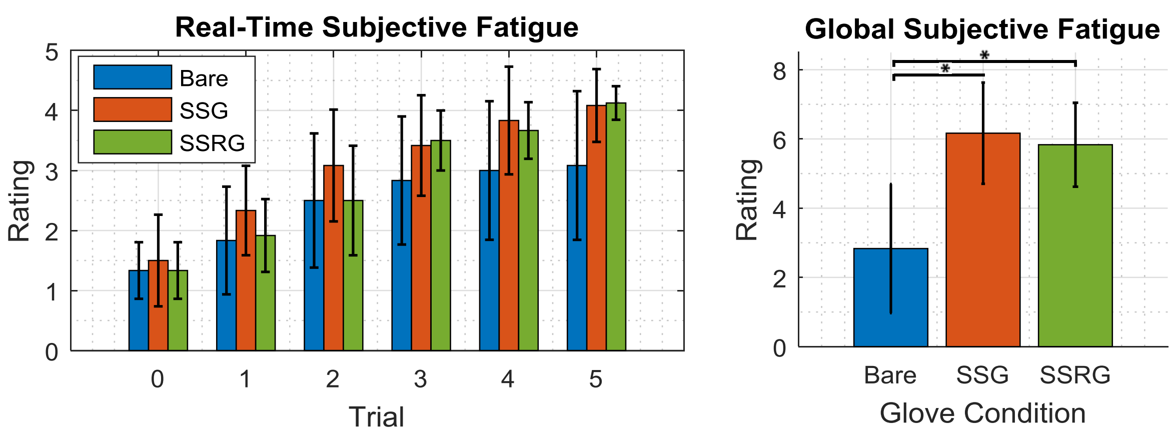

Figure 5: Subjective fatigue ratings as a measure of psychological perception of fatigue. Average (standard deviation bars) real-time subjective fatigue ratings, (collected after each trial 0-5) and global fatigue ratings (collected at the end of the experiment) during barehanded (Bare), SSG, and SSRG work. Ratings during Trials 0-5 were based on a 5-point scale while global ratings were based on an 8-point scale. Real-time and global ratings were analyzed separately. Statistical significance ($p<0.05$) are indicated (*).

C. Neuromuscular Fatigue

The MF metric proved to be unsatisfactory in quantifying neuromuscular fatigue in the majority of muscles and glove conditions. During fatigue, MF should decrease over subsequent trials compared to the unrested state (Trial 0), however, in many instances MF increased or exhibited odd, non-monotonic behavior. This phenomena occurred both when MF was averaged across subjects (Fig. 6) as well as when analyzed for subjects individually (Fig. 7). As a result, statistical analyses for the MF metric will not be reported and MF will not be used to draw conclusions about neuromuscular fatigue.

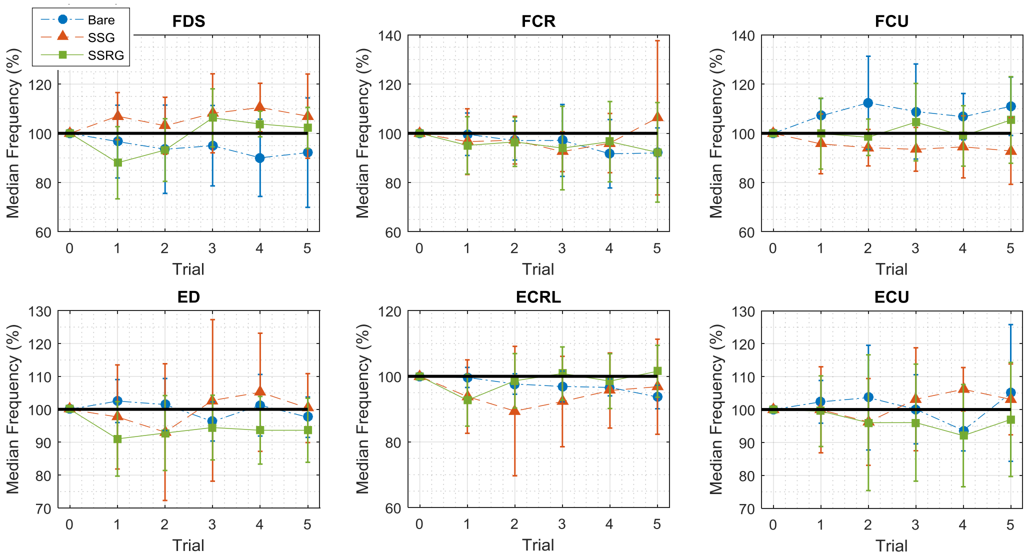

Figure 6: Trends in neuromuscular fatigue. Average (standard deviation bars) changes in fatigue during the experiment, as assessed by the change in y-intercept of the MF over the six trials, for the FDS, FCR, FCU, ED, ECRL, and ECU during barehanded (Bare), SSG, and SSRG work.

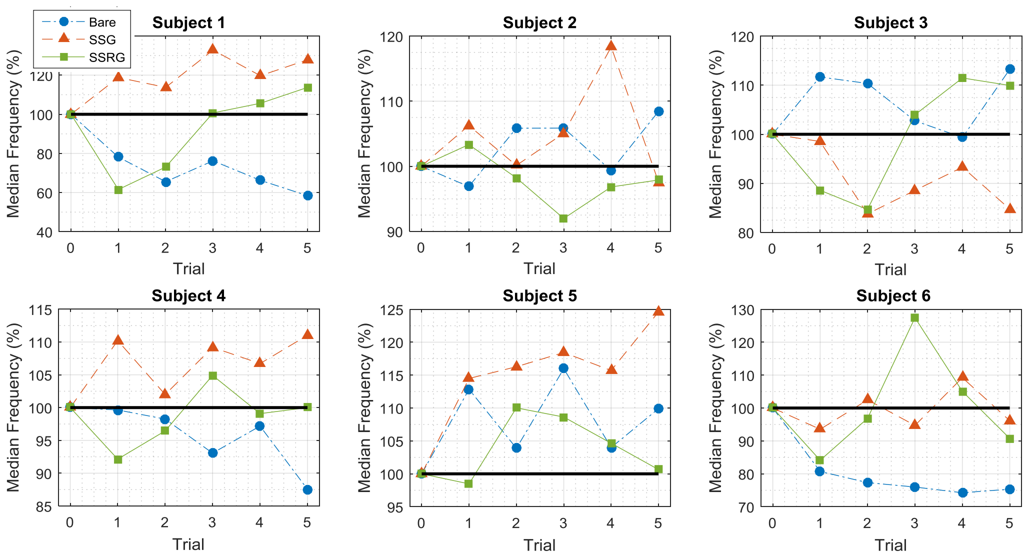

Figure 7: Subject variation in neuromuscular fatigue of the FDS. Change in y-intercept of the MF over the six trials for all subjects' FDS during barehanded (Bare), SSG, and SSRG work.

D. Correlations

For the isometric task, significant, moderately-strong positive correlations were detected for global subjective fatigue and FDS iEMG, r =0 .71, p = 0.005, R^2 = 0.51, global subjective fatigue and FCR iEMG, r = 0.78, p = 0.004, R^2 = 0.61, and global subjective fatigue and ECRL iEMG, r = 0.74, p = 0.023, R^2 = 0.55 (Table 2). For the dynamic task, significant, moderately-strong positive correlations were detected for global subjective fatigue and FDS iEMG, r = 0.66, p = 0.012, R^2 = 0.44, and global subjective fatigue and FCR iEMG, r = 0.75, p = 0.006, R^2 = 0.56, global subjective fatigue and ECRL iEMG, r = 0.86, p = 0.58, R^2 = 0.74 (Table 2).

Significant, strong positive correlations were detected for FDS iEMG during the isometric task and FDS iEMG during the dynamic task, r = 0.93, p < 0.0001, R^2 = 0.86, FCR iEMG during the isometric task and FCR iEMG during the dynamic task, r = .84, p = 0.003, R^2 = 0.71, and ECRL iEMG during the isometric task and ECRL iEMG during the dynamic task, r = .88, p = 0.014, R^2 = 0.78 (Table 3). A significant moderately-strong positive correlation was detected for FCU iEMG during the isometric task and FCU iEMG during the dynamic task, r = .46, p = 0.009, R^2 = 0.68 (Table 3).

For the isometric task, significant strong positive correlations were detected for FDS iEMG and FCR iEMG, r = 0.94, p < 0.0001, R^2 = 0.89, and for ED iEMG and ECRL iEMG, r = 0.84, p = 0.003, R^2 = 0.71 (Table 4). Significant, moderately strong positive correlations were detected for ED iEMG and ECU iEMG, r = 0.71, p = 0.004, R^2 = 0.50, and ECRL iEMG and ECU iEMG, r = 0.68, p = 0.006, R^2 = 0.46 (Table 4). For the dynamic task, a significant strong positive correlations was detected for FDS iEMG and FCR iEMG, r = 0.86, p < 0.0001, R^2 = 0.86 (Table 4).

	iEMG Dynamic	
iEMG Isometric	R^2	P Value
FDS-FDS	0.86	<0.0001
FCR-FCR	0.71	0.000
FCU-FCU	0.46	0.009
ED-ED	0.14	0.571
ECRL-ECRL	0.78	0.014
ECU-ECU	0.06	0.375

Table 4: Conditional R-squared values for the relationship between neuromuscular effort (iEMG) during isometric and dynamic tasks. Values are given for the FDS, FCR, FCU, ED, ECRL, and ECU muscles.

	Global Subjective Fatigue			
	Isometric Task		Dynamic Task	
iEMG	R^2	P Value	R^2	P Value
FDS	0.51	0.005	0.44	0.012
FCR	0.61	0.004	0.56	0.006
FCU	0.12	0.181	0.01	0.649
ED	0.24	0.048	0.18	0.578
ECRL	0.55	0.049	0.74	0.584
ECU	0.33	0.023	0.03	0.468

Table 2: Conditional R-squared values for the relationship between global subjective fatigue ratings and neuromuscular effort (iEMG). Values are given for the FDS, FCR, FCU, ED, ECRL, and ECU muscles during isometric and dynamic tasks.

	iEMG			
	Isometric Task		Dynamic Task	
iEMG	R^2	P Value	R^2	P Value
FDS-FCR	0.89	<0.0001	0.74	<0.0001
FDS-FCU	0.18	0.090	0.24	0.048
FCR-FCU	0.04	0.014	0.19	0.086
ED-ECRL	0.71	0.003	0.88	0.895
ED-ECU	0.50	0.004	0.05	0.467
ECRL-ECU	0.46	0.006	0.00	0.879

Table 3: Conditional R-squared values for the relationship between neuromuscular effort (iEMG) of different muscles. Values are given for the FDS, FCR, FCU, ED, ECRL, and ECU muscles during isometric and dynamic tasks.

IV. Discussion

The overall goals of this study were to i) quantify the neuromuscular modulations that occur in response to wearing a space suit glove (SSG) during a fatiguing task, and ii) determine the efficacy of Spacesuit RoboGlove (SSRG) in reversing the adverse neuromuscular modulations and restoring altered muscular activity to barehanded (Bare) levels. Although the metric used to investigate neuromuscular fatigue provided inconclusive results, the quantitative index of expended neuromuscular effort could be used as a precursor to fatigue. Neuromuscular effort provides insight into how the magnitude of each muscle's contribution to a given work output changes under different glove conditions. Thus, by noticing a comparative reduction in neuromuscular effort of a muscle during a given glove condition, for example, an inference could be made that this muscle is less prone to fatiguing.

A. Neuromuscular Effort

1. Neuromuscular Effort during a Constant-Force Grasp

The isometric constant-force grasp is a movement that heavily recruits all extrinsic forearm muscles to both flex the fingers and stabilize the position of the wrist. When averaged across subjects, the SSG condition required all flexor and extensor muscles to increase their expended effort compared to the barehanded condition. The higher iEMG values for the flexor muscles (FDS, FCR, and FCU) while wearing the SSG reflect the encumbrance of a space suit glove on flexing the fingers. The thickness of the multi-layered SSG design combined with the 4.3 psi pressure differential, which naturally works to keep the SSG fingers in an extended position, make it difficult to flex the fingers and grasp a tool against the palm of the glove. As a result, subjects had difficulty wrapping their fingers around the hand dynamometer and maintaining a consistent grip while wearing the SSG. Furthermore, the thickness of the palmer region of the SSG resulted in the hand dynamometer resting closer to the distal segments of the fingers, which significantly reduces the leverage of the fingers. In order to produce a grip force, more activation from the FCR and FCU may have been recruited to slightly flex the wrist and generate a force against the hand dynamometer.

When averaged across subjects, the SSRG showed a reduction in flexor muscular effort for the FDS and FCR compared to the SSG condition, although statistical significance was not achieved. The SSRG did not restore altered muscular effort to barehanded levels when averaged across subjects. When analyzing each subject's performance individually, however, we can see that some subject's responded positively to the robotic grip assistance of the SSRG while others displayed less favorable responses. The percentage of subjects who experienced reduced muscular effort using the SSRG compared to the SSG was 50% for FDS and FCU, and 67% for FCR. An example of this variation can be seen in the top left subfigure of Fig. 4, where Subjects 1 and 3 showed large decreases in FDS iEMG while wearing SSRG compared to SSG, Subject 2 showed a moderate decrease, and Subjects 4-6 showed slight increases.

The higher iEMG values for the extensor muscles (ED, ECRL, ECU) while wearing the SSG, compared to barehanded work, could be due to a combination of factors. Firstly, a power grasp requires the wrist to be stabilized as the fingers flex. When the flexors start exerting more effort to maintain or increase force output, the extensors must exert more effort to maintain wrist posture (i.e. prevent the wrist from flexing). Thus, to maintain a constant force output without changing wrist posture, both flexors and extensors must be active. Secondly, maximum grip force is achieved with the wrist at about 30 degrees of extension.[31] The more the wrist angle deviates from this optimal position, the less efficient the flexor and extensor muscles are in producing a grip force. Post-hoc analysis of video recordings taken during the experiments showed that a subject's natural wrist angle is slightly more flexed while wearing the SSG compared to the barehanded condition in which the wrist angle was at zero degrees of flexion (i.e. the hand was in line with the forearm). Thus, the extensor muscles were stretched further away from their optimal force generating position while wearing the SSG, causing increased activations to achieve the same prescribed force output.

When averaged across subjects, the SSRG showed an increase in the effort of all extensor muscles compared to the SSG condition, effectively amplifying the adverse neuromuscular modulations imposed on subjects by the SSG. There was much less subject variation in extensor muscle behavior. The percentage of subjects who experienced reduced muscular effort during the isometric grasping task using the SSRG compared to the SSG was 0% for ED and ECRL, and 17% for ECU. An example of this subject consistency can be seen in the bottom left subfigure of Fig. 4, where all subjects showed an increase in ED iEMG while wearing SSRG compared to SSG.

The variation in subject response while using the SSRG compared to the SSG could be due to two factors. Firstly, some subjects reported that SSRG robotic assistance seemed to be inconsistent during the isometric, constant-force task. They felt that sometimes the motors of the SSRG would engage and provide assistance while other times it felt like no assistance was being provided. The quality of the FSR output signal, as well as difficulties subjects faced in aligning the area of the glove that contains the FSR over the hand dynamometer during grasping, could have caused this fallibility. Secondly, the SSRG contains a palm bar that anchors the conduits routing the tendons from the SSRG fingers to the motors (Fig. 1). This palm bar creates a thicker palmar region in the SSRG compared to the SSG, which may have affected some subjects' ability to firmly grasp the hand dynamometer without slippage. As a result, the fingers couldn't provide as much leverage toward force generation, so more effort was required by the supplementary muscles to hold the device.

2. Neuromuscular Effort during a Cyclic-Gripping Task

The dynamic, cyclic-gripping task is a movement that heavily recruits the finger flexor and extensor muscles (FDS and ED, respectively), while also requiring assistance from the wrist stabilizer muscles (FCR, FCU, ECRL, ECU). When averaged across subjects, the SSG condition required all flexor muscles to increase their expended effort and all extensor muscles to decrease their expended effort compared to the barehanded condition. As with the isometric task, the higher iEMG values for the flexor muscles (FDS, FCR, and FCU) while wearing the SSG reflect the encumbrance that a space suit glove places on flexing the fingers. This impedance is a result of the three-layered glove design combined with the 4.3 psi pressure differential.

When averaged across subjects, the SSRG showed a reduction in flexor muscular effort for the FDS and FCR compared to the SSG condition, although statistical significance was not achieved. The SSRG did not restore altered muscular effort to barehanded levels when averaged across subjects. As with the isometric task, individual subjects responded differently to the robotic grip assistance of the SSRG. The percentage of subjects who experienced reduced muscular effort using the SSRG compared to the SSG was 83% for FDS and FCR, and 67% for FCU. An example of this variation can be seen in the top right subfigure of Fig. 4, where all but Subject 5 showed decreases in FDS iEMG.

The lower iEMG values for the extensor muscles (ED, ECRL, ECU) while wearing the SSG compared to barehanded work are consistent with results in the literature reporting higher levels of fatigue in a forearm extensor muscle (ECU) while performing a task barehanded compared to when wearing a space suit glove pressurized to 4.3 psi.[2,13] These results are due to the tendency of the spacesuit to return to an equilibrium position when under pressure. For the fingers, this equilibrium position is when the fingers are fully extended. Thus, the suit naturally reduces the amount of effort needed to extend the fingers. Notably, four out of six subjects showed decreased muscular effort of the ED during SSG work compared to barehanded work (Fig. 4).

When averaged across subjects, the SSRG showed an increase in the effort of all extensor muscles compared to the SSG condition, effectively reversing the favorable effects of the 4.3 psi pressure differential. The percentage of subjects who experienced reduced muscular effort during the dynamic grasping task using the SSRG compared to the SSG was 33% for ED and ECU, and 0% for ECRL. An example of this subject consistency can be seen in the bottom right plot of Fig. 4, where all subjects showed an increase in ED iEMG while wearing SSRG compared to SSG. Although SSRG does not reduce extensor muscular effort compared to SSG, it also does not significantly increase muscular effort past barehanded levels for all subjects. iEMG levels of the ED were lower while using the SSRG compared to barehanded work for 4 out of six of the subjects. The remaining two subjects seemed to have adverse effects to the control strategy of SSRG.

Variation in subject response to the SSRG could be due to the nature of the control strategy and quality of the controller calibration. The SSRG only provides active assistance in flexion. To extend the fingers, the subject needs to backdrive the motors, making extension a more intentional and controlled movement than during SSG use. This control strategy depends on the change in subject finger angle and the output of the string potentiometer, which measures the relative linear position of the robotic tendon. An optimal controller will sense a change in angle and initiate motor actuation with minimal time delay. If the motor moves before the subject changes their joint angle this is called leading, whereas if the motor moves well after the subject changes their joint angle this is called lagging. Some subjects reported that they had to work slightly against the SSRG when moving their fingers, which means that the controller was lagging these subject's intended movement. Subjects 3 and 4 in Fig. 4 are examples of this phenomena. Subjects 1, 5, and 6, however, did not feel resistance applied by the SSRG and most likely had a controller that was tuned to slightly lead their intended movements. Another factor playing into subject variation in response to the SSRG could be the amount of time each subject had to practice manipulating the hand dynamometer and dynamic gripper whilst wearing the actuated SSRG. Although subjects were granted a few minutes to practice operating the SSRG before the experiment began, subject feedback indicated that it may not have been enough to eliminate learning effects that occurred as the experiment progressed. Thus, subjects that showed adverse neuromuscular reactions to the SSRG could have needed more time to practice operating the glove in an optimal manner.

3. *Additional Findings on Neuromuscular Effort*

During all glove conditions, subjects reported that it was difficult to maintain a neutral forearm posture such that their palm was facing to the left and thumb was pointing toward the ceiling. Since the arm holes of the glovebox cannot be adjusted to fit the shoulder breadth of an individual subject, the glovebox forces the subject into a posture that naturally pronates the forearm. As a result, the subjects felt like they were actively working to supinate their forearm to maintain the neutral posture. This could explain the larger than expected iEMG values for the FCU and ECU, which are secondary supinator muscles. Furthermore, the large standard errors for the FCR, ECRL, and ECU muscles in the SSG and SSRG conditions could be accounted for by subject variation in wrist posture. Though a neutral wrist posture was enforced, subjects had the tendency of adopting a radial deviated or ulnar deviated wrist posture depending on their strategy for holding the hand dynamometer in the gloves. Deviation of the wrist will affect whether the muscles on the ulnar side (FCU and ECU) or radial side (FCR and ECRL) of the wrist are contributing more toward force output and posture maintenance. Lastly, at the conclusion of each glove condition, subjects reported feeling burning in their extensor muscles. This feedback seemed somewhat odd considering the experimental tasks were designed to induce fatigue in the flexor muscles. After further consideration and post-hoc video analysis, however, it was concluded that the slightly flexed position of the wrist when wearing either the SSG or SSRG causes the extensors to be in a stretched position. As previously stated, the more the wrist deviates from its optimal power grasp position (i.e. 30 degrees of extension) the more effort the extensors have to exert to achieve a certain force output or remain in a given posture.

B. Subjective Fatigue

Subjects felt like they fatigued less while wearing the SSRG compared to SSG during the first half of the work phase (Trials 0-2) (Fig. 4). In fact, subjects felt like they fatigued at approximately the same rate while using the SSRG compared to barehanded work during these first three trials. This may indicate that the SSRG was helpful in reducing fatigue compared to SSG for short periods (up to three minutes) of intense, fatiguing work. Beyond this point (i.e. Trials 3-5), the effects of the encumbering SSRG glove design overcame the benefits robotic grip assistance resulting in subject perception of fatigue as approximately equivalent for the SSG and SSRG. The smaller increase in subjective fatigue over all trials for the barehanded condition compared to the SSG and SSRG conditions is in agreement with results from a previous study.[2,13]

Although real-time subjective fatigue ratings were not significantly higher for either SSG or SSRG compared to barehanded work, subject feedback revealed that their perception of a 5 rating (complete fatigue) was slightly different for the barehanded condition compared to either glove condition. In retrospect, they may have rated the barehanded condition with lower values. Thus, it is difficult to make an objective comparison between either glove condition and barehanded work. This finding reveals an inherent problem in evaluating the efficacy of a treatment condition with a qualitative analog scale. By assessing neuromuscular effort and/or fatigue using quantitative methods, such as sEMG, a more reliable comparison can be made across conditions. Nevertheless, subjective scales are an important measure because they reveal the psychological effects of treatment conditions on subjects' perception of their own fatigue. Although the subjective fatigue rating does not provide physiological meaning, the psychological effects of a robotic assist device could potentially improve an astronauts endurance and performance output. For instance, the SSRG could increase the neuromuscular effort of a subject according to sEMG, however, if subject's believes that the robotic assistance is aiding his/her ability to complete a task, the mere presence of the SSRG could benefit this individual.

For the global fatigue rating that was collected at the end of each session, the barehanded condition resulted in significantly lower perceptions of fatigue compared to both the SSG and SSRG when averaged across subjects. There was virtually no difference between SSG and SSRG conditions when averaged across subjects. When resolved into individual subject responses, two subjects rated the SSRG as less fatiguing than the SSG, three subjects rated the SSRG equally as fatiguing as the SSG, and one subject rated the SSRG as more fatiguing than the SSG. As with the real-time subjective fatigue ratings, the global fatigue rating is a course measure that lacks the reliability of a quantitative physiological metric.

C. Neuromuscular Fatigue

1. Neuromuscular Fatigue Analysis

The MF metric was derived to evaluate neuromuscular fatigue induced when wearing the SSG and determine the efficacy of SSRG in reducing this fatigue. We expected to see that the SSG was more fatiguing for the flexor muscles than barehanded work, the SSRG was less fatiguing for the flexors than the SSG, and the SSG was less fatiguing on the extensors than both SSRG and barehanded work. This fatigue would be quantified by the decrease in MF over trials compared to the rested state in Trial 0. Since the metric displayed erratic trends that were infrequently indicative of fatigue (i.e. MF either increased or behaved non-monotonically over the trials), it was inappropriate to use MF as comparative measure to draw conclusions about the different glove conditions.

For example, FDS was expected to show signs of fatigue during all three of the glove conditions. When averaged across subjects, the barehanded condition showed a decreasing MF slope. However, SSG showed an increasing slope and SSRG showed a non-monotonic behavior (Fig. 6). At face value, these results would imply that the subjects fatigued more during the barehanded condition compared to either glove condition, a phenomenon that seems incorrect especially for the SSG condition. Since the standard errors of MF are large, indicating appreciable variation across subjects, each individual subject's FDS muscle was analyzed (Fig. 7). Nevertheless, similar oddities in MF trends were present within subjects. Fatiguing trends (i.e. decreasing MF) were only seen in three subjects during the barehanded condition, one subject during the SSG condition, and no subjects for the SSRG condition. All subjects displayed non-monotonic behavior in MF for the SSRG condition.

2. Analogous Studies in the Literature

The experimental design of the present study was informed by an analogous study in the literature. The study by O'Hara et al.[2,13] analyzed space suit glove fatigue using the same protocol as used in the present experiment and reported very clear trends in fatigue for the FDS and ECU muscles. It is possible that a few modifications made to protocol of the present experiment could explain why it failed to reveal the same trends in fatigue. Firstly, the experiment in O'Hara et al. prescribed 45 gripping cycles per 45 s (0.5s to open, 0.5s to close) during the dynamic contraction task. Pilot studies performed before the present experiment were carried out at the same 1 Hz cadence, however, this pace proved to be too fatiguing to maintain with the SSG and prevented subjects from finishing the experiment. A 0.5 Hz cadence was instead prescribed for this experiment, such that 30 gripping cycles per minute (1s to open, 1s to closewere performed, so that subject's would fatigue at a slower rate and be able to finish the experiment. As a result, the subjects in O'Hara's experiment may have experienced more intense fatigue that was reflected in the MF metric. Secondly, O'Hara used a BTE device gripping fixture that was set to 20% of the subjects' MVC for the dynamic gripping task. For this study, a commercial gripper set at 20% MVC was used for a pilot test, however, subjects were again becoming too fatigued and faced difficulties maintaining a firm grasp on the device. As a result, a custom built dynamic gripper was fabricated to provide a lighter resistance and be more compatible with the spacesuit glove. The device was set to about 5lbs of resistance for all subjects, which was just high enough for some subjects to reach maximum fatigue (i.e. 5 on the real-time subjective fatigue rating scale) by the end of the experiment when wearing the SSG. Lastly, subjects in this experiment faced difficulties quickly transitioning between the hand dynamometer and the dynamic gripper, often taking 5 to 8 s to complete. There was no mention of similar difficulties in the study by O'Hara et al. If the subjects in O'Hara et al. did not use as much time to transition between devices, it would have reduced the amount physiological recovery time for the muscles and ultimately make for a cleaner and more consistent MF metric. Further details about physiological recovery are discussed below.

Clancy et al.[32] also conducted a study similar to the present experiment that attempted to monitor forearm fatigue using MF. While barehanded, subjects exerted cyclic-gripping contractions interspersed with isometric contractions using a hand dynamometer. The authors found no statistical trends in MF and concluded that these metrics may not be well suited for detecting fatigue in long-duration, force-varying contractions interspersed with isometric holds. Clancy's work supports the results of the present study but contradicts the validity of the findings in O'Hara et al.[2,13]

3. Factors Affecting Neuromuscular Fatigue Results

All subjects claimed that they experienced a burning sensation in their forearms, providing evidence that their muscles were indeed fatiguing during the present experiment. Thus, other confounding factors affecting the MF metric must have been present. One such factor concerns the postural and movement constraints imposed by the glovebox design. The distance between the arm apertures of the glove box is set at a fixed width. As a result, the subjects' shoulder breadths did not align directly with these holes, causing their shoulders to abduct, elbows to bow outward, and forearms to naturally pronate (i.e. rotate such that the palm is facing downward). This restricted subject arm movement and made it difficult to maintain a neutral wrist posture. The volumetric workspace of the glovebox is also relatively small, leaving very little space available to move the arms and handle equipment inside of the glovebox while wearing the SSG and SSRG. Consequently, subjects could not use their left hand to transfer the hand dynamometer and dynamic gripper to the right hand in a quick or efficient manner. Subjects were forced to use their right hand to pick up and put down the devices causing them to change the posture of their forearm from trial to trial. Although preventative measures were enforced in the experimental protocol to reduce this movement, it was inherently unavoidable. These forearm posture changes to accommodate the restrictive glovebox are believed to be the most contributing factor to the inadequate fatigue metrics. The location of an electrode with respect to motor points in the muscle directly impacts the spectral characteristics (e.g. the MF metric) of the sEMG signal.[33] An electrode, once adhered to the skin, remains stationary on the surface of the forearm. When a person changes his/her posture, the muscles will move underneath the skin with respect to the fixed electrode. As a result, the portion of the muscle from which the electrode is collecting sEMG is different from one posture to the next, resulting in different sEMG spectral properties at each posture. For example, regardless of whether or not a muscle is fatiguing, the muscle could display an MF of 90 Hz with the forearm in a neutral position and an MF of 100 Hz when slightly pronated. In order to obtain an accurate and consistent portrayal of muscle fatigue, it is important to collect sEMG from the same portion of the muscle at every trial so that a decreasing trend in MF can be seen.

A second confounding factor affecting the MF metric could be a combination of the aforementioned movement constraints and the ergonomic incompatibility of the tools used in the experiment with the SSG and SSRG. The contours of the dynamic gripper and hand dynamometer did not conform well with the palmar region of the space suit gloves, causing the devices to slip out of the subjects' hands. This made it difficult for subjects to manipulate and get a firm power grasp on the devices in a timely manner. An 8 s device transfer cutoff time had to be enforced to encourage the subjects to transition between devices as quickly as possible. Since physiological recovery occurs almost instantaneously after a fatiguing exercise ceases, this 8 s period of rest between when the muscles are being fatigued by the dynamic contractions and when the sEMG is being measured during the isometric contractions could have masked and reversed the physiological fatigue that was induced during dynamic gripping. Thus, the sEMG data from the isometric squeeze of the hand dynamometer may not have been good snap-shot representation of the subjects' fatigued state and produced higher than expected MF values.

Lastly, changes in body temperature during the experiment could have presented another confounding factor. The amount of effort it took to perform the experimental protocol while wearing the SSG and SSRG, as well as the material thickness and lack of breathability inside the SSG and SSRG, caused the subjects to become very warm, a handful even breaking a sweat. These increases in body temperature and skin properties could have affected the integrity of the MF fatigue metric during the gloved conditions. A study performed on exercise using a bicycle ergometer[34] revealed that increases in subject body temperature caused the MF to increase, counteracting the decreasing MF trend that occurs during fatigue.

D. Correlations

The global subjective fatigue rating correlated well with the neuromuscular effort expended by the FDS, FCR, and ECRL during both isometric and dynamic task, and the FCU during the dynamic task. The strong correlations between iEMG during the isometric and dynamic tasks for FDS, FCR, ECRL, and moderately-strong correlation for FCU shows that it feasible to predict the neuromuscular effort required by the flexor muscles during the dynamic task based on their effort during the isometric task, and vice versa. Thus, if experimental resources are limited and researchers are interested in analyzing strictly flexor activity during gloved conditions, either an isometric or dynamic task can be selected and inferences can be made about the trends muscle performance for the unchosen task. The weak correlations between iEMG during the isometric and dynamic tasks for ED and ECU, however, make this type of predictive analysis ineffective for the extensor muscles.

To determine the minimal number of sEMG electrodes to use during future experiments that may lack experimental resources, correlations between muscles within a task were performed. Strong positive correlations between the iEMG of muscles indicate that the trends in neuromuscular effort exerted by these muscles are similar. As a result, either of the muscles could be selected for analysis and the behavior of the unchosen muscle under different glove conditions could be predicted. Thus, for both the isometric and dynamic tasks, either FDS or FCR and ED or ECRL could be selected for analysis. For the isometric task, either ED and ECRL, or ED and ECU could be selected. A possible minimal set of sEMG electrodes for the isometric task could include FDS, ED, and ECU. For the dynamic task, the set could consist of sEMG electrodes for the FDS, FCU, ED, and ECU.

E. Implications of Findings

This is the first study of its kind to use sEMG to quantify the effects of robotic grasp assistance on spacesuit glove use. Although a previous study[13] has used sEMG to quantify the effects of pressurized EVA gloves on fatigue and work, only two muscles of the forearm were evaluated. Our study, targeting six muscles and capturing most flexors and extensors of the wrist and fingers, painted a more comprehensive picture of how astronauts exert effort while wearing EVA gloves during different types of tasks. Accordingly, results from this study improved the understanding of astronaut-spacesuit interaction by identifying the forearm muscles that exert the most effort and are, therefore, most prone to fatigue and in need of force augmentation. These results can help inform engineers how to improve the design of space suit gloves and space suit glove robotic-assist devices. Possible improvements to the SSRG include i) mechanical design changes to the conduit palm bar by either reducing its thickness or relocating it to the dorsal side of the glove, ii) improving the signal quality of the force sensitive resistors (FSRs) responsible for triggering the isometric constant-hold grasp so that the motor response is more consistently triggered and less jerky, iii) implementation of a wrist splint in both the SSG and SSRG to stabilize the wrist in a more extended, force-optimal position, and iv) adjustments to the controller calibration strategy using the string potentiometers and/or longer calibration sessions so that the motors err on the side of slightly leading the subjects intended motion, rather than lagging.

V. Conclusion

By augmenting finger flexion, the SSRG successfully reduced the neuromuscular effort needed to close the fingers of the space suit glove in more than half of subjects during two types of tasks. However, the SSRG required more neuromuscular effort to extend the fingers compared to a conventional SSG in many subjects. Psychologically, the SSRG aided subjects in feeling less fatigued during short periods of intense work compared to when wearing the SSG. The results of this study reveal the capability and potential of the SSRG as a grasp-assist device that can improve astronaut performance and reduce the risk of injury by offsetting neuromuscular effort. Modifications to the experimental protocol are needed, however, to improve the outcome of the neuromuscular fatigue metrics and determine the effectiveness of SSRG in increasing astronaut endurance. Nevertheless, these findings will improve the understanding of astronaut-spacesuit interaction and provide direction toward designing improved spacesuit gloves and robotic-assist devices, like the SSRG.

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References

[1]Rajulu, S., M. Mesloh, S. Thompson, S. England, and L. Benson. *The Effects of Extravehicular Activity (Eva) Glove Pressure on Hand Strength*. in *3rd International Conference on Applied Human Factors and Ergonomics*.

[2]Ohara, J.M., M. Briganti, J. Cleland, and D. Winfield, *Extravehicular Activities Limitations Study.* NASA Contractor Report AS-EVAL-FR-7801, 1988. **2**.

[3]Bishu, R.R. and G. Klute, *The Effects of Extra Vehicular Activity (Eva) Gloves on Human Performance.* International Journal of Industrial Ergonomics, 1995. **16**(3): p. 165-174.

[4]Basmajian, J.V. and C.J. De Luca, *Muscles Alive.* Muscles alive: their functions revealed by electromyography, 1985. **278**: p. 126-126.

[5]Sorenson, E.A., R.M. Sanner, and C.U. Ranniger. *Experimental Testing of a Power-Assisted Space Suit Glove Joint*. in *Systems, Man, and Cybernetics, 1997. IEEE International Conference on Computational Cybernetics and Simulation*.

[6]Charvat, C.M., J. Norcross, C.R. Reid, and S.M. McFarland. *Spacesuit Glove-Induced Hand Trauma and Analysis of Potentially Related Risk Variables*. in *45th International Conference on Environmental Systems*.

[7]Viegas, S.F., D. Williams, J. Jones, S. Strauss, and J. Clark, *Physical Demands and Injuries to the Upper Extremity Associated with the Space Program.* The Journal of Hand Surgery, 2004. **29**(3): p. 359-366.

[8]Rogers, J.M., B.J. Peters, E.A. Laske, and E.R. McBryan. *Robotically Assisted Eva Gloves for Iss and Exploration*. in *ISS Research and Development Conference*. 2016. San Diego, CA.

[9]Rogers, J.M., B.J. Peters, E.A. Laske, and E.R. McBryan, *Development and Testing of Robotically Assisted Extravehicular Activity Gloves*, in *47th International Conference on Environmental Systems*. 2017: Charleston, SC.

[10]Diftler, M., et al. *Roboglove - a Robonaut Derived Multipurpose Assistive Device*. in *International Conference on Robotics and Automation*.

[11]Bigland-Ritchie, B. and J.J. Woods, *Changes in Muscle Contractile Properties and Neural Control During Human Muscular Fatigue.* Muscle & Nerve, 1984. **7**(9): p. 691-699.

[12]Luca, D. and J. Carlo, *Myoelectrical Manifestations of Localized Muscular Fatigue in Humans.* Critical Reviews in Biomedical Engineering, 1983. **11**(4): p. 251-279.

[13]Roy, S.H. and J.M. Oh́ara, *Evaluation of Forearm Fatigue During Eva Pressure Glove Work.* Work, 1997. **8**(2): p. 157-169.

[14]Petrofsky, J.S., *Quantification through the Surface Emg of Muscle Fatigue and Recovery During Successive Isometric Contractions.* Aviation, Space, and Environmental Medicine, 1981. **52**(9): p. 545-550.

[15]Farina, D., L. Fattorini, F. Felici, and G. Filligoi, *Nonlinear Surface Emg Analysis to Detect Changes of Motor Unit Conduction Velocity and Synchronization.* Journal of Applied Physiology, 2002. **93**(5): p. 1753-1763.

[16]McManus, L., X. Hu, W.Z. Rymer, M.M. Lowery, and N.L. Suresh, *Changes in Motor Unit Behavior Following Isometric Fatigue of the First Dorsal Interosseous Muscle.* Journal of Neurophysiology, 2015. **113**(9): p. 3186-3196.

[17]Khalil, T.M., *An Electromyographic Methodology for the Evaluation of Industrial Design.* Human Factors: The Journal of the Human Factors and Ergonomics Society, 1973. **15**(3): p. 257-264.

[18]Komi, P.V. and J.H.T. Viitasalo, *Signal Characteristics of Emg at Different Levels of Muscle Tension.* Acta Physiologica Scandinavica, 1976. **96**(2): p. 267-276.

[19]Kuorinka, I., et al., *Standardised Nordic Questionnaires for the Analysis of Musculoskeletal Symptoms.* Applied Ergonomics, 1987. **18**(3): p. 233-237.

[20]Farina, D. and R. Merletti, *Comparison of Algorithms for Estimation of Emg Variables During Voluntary Isometric Contractions.* Journal of Electromyography and Kinesiology, 2000. **10**(5): p. 337-349.

[21]Merletti, R. and L.R.L. Conte, *Advances in Processing of Surface Myoelectric Signals: Part 1.* Medical and Biological Engineering and Computing, 1995. **33**(3): p. 362-372.

[22]Roy, S.H., C.J. De Luca, and J. Schneider, *Effects of Electrode Location on Myoelectric Conduction Velocity and Median Frequency Estimates.* Journal of Applied Physiology, 1986. **61**(4): p. 1510-1517.

[23]Saitou, K., T. Masuda, D. Michikami, R. Kojima, and M. Okada, *Innervation Zones of the Upper and Lower Limb Muscles Estimated by Using Multichannel Surface Emg.* Journal of Human Ergology, 2000. **29**(1/2): p. 35-52.

[24]Baratta, R.V., M. Solomonow, B.H. Zhou, and M. Zhu, *Methods to Reduce the Variability of Emg Power Spectrum Estimates.* Journal of Electromyography and Kinesiology, 1998. **8**(5): p. 279-285.

[25]Clancy, E.A., E.L. Morin, and R. Merletti, *Sampling, Noise-Reduction and Amplitude Estimation Issues in Surface Electromyography.* Journal of Electromyography and Kinesiology, 2002. **12**(1): p. 1-16.
[26]Semmlow, J., *Biosignal and Biomedical Image Processing. Matlab-Based Application.* Marcel Dekker. USA, 2004. **443**: p. 367-396.
[27]Paiss, O. and G.F. Inbar, *Autoregressive Modeling of Surface Emg and Its Spectrum with Application to Fatigue.* IEEE Transactions on Biomedical Engineering, 1987(10): p. 761-770.
[28]Burg, J.P. *Maximum Entropy Spectral Analysis*. in *37th Annual International Meeting.*
[29]Merletti, R., M. Knaflitz, and C.J. De Luca, *Myoelectric Manifestations of Fatigue in Voluntary and Electrically Elicited Contractions.* Journal of Applied Physiology, 1990. **69**(5): p. 1810-1820.
[30]Team, R.C., *R: A Language and Environment for Statistical Computing*. 2016.
[31]Neumann, D.A., *Kinesiology of the Musculoskeletal System: Foundations for Rehabilitation*. 2013: Elsevier Health Sciences.
[32]Clancy, E.A., M.V. Bertolina, R. Merletti, and D. Farina, *Time-and Frequency-Domain Monitoring of the Myoelectric Signal During a Long-Duration, Cyclic, Force-Varying, Fatiguing Hand-Grip Task.* Journal of Electromyography and Kinesiology, 2008. **18**(5): p. 789-797.
[33]Luca, D. and J. Carlo, *The Use of Surface Electromyography in Biomechanics.* Journal of Applied Biomechanics, 1997. **13**: p. 135-163.
[34]Petrofsky, J.S., *Frequency and Amplitude Analysis of the Emg During Exercise on the Bicycle Ergometer.* European Journal of Applied Physiology and Occupational Physiology, 1979. **41**(1): p. 1-15.